大型ロケット用液化水素エンジンの故障解析および信頼度評価に関する研究

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論 文 内 容 要 旨

Newly developed launch vehicles in the world are mainly propelled by cryogenic engines, which use liquid hydrogen and liquid oxygen as propellants for the reasons of high propulsive performance of their combustion gases. However, because of low temperature and low density of liquid hydrogen as compared with other propellants, there are a lot of problems to be solved for development of a large size high pressure hydrogen engine, such that it is very easy to boil so that excessive cavitations sometimes occur in liquid hydrogen pump, extremely high power is required for hydrogen turbo-pump therefore it induces severe fluid vibrations which result in fatigue damage to limited life design parts, and cryogenic hydrogen causes brittleness of materials and thermal fatigue.

For the purpose of accomplishing launch missions to put payloads into the specified earth orbits, launch vehicles accelerate space-crafts up to ultra-high speed in the concrete 8km/sec. Accordingly, launch vehicles are required extremely light structures and tremendously high powers. Consequently, developments of launch vehicles in the world belong to frontier technology area where the success rate of newly developed launch vehicles is statistically only 85% and most of causes of launch anomalies are occupied by engine troubles. Generally speaking, space-crafts are very expensive, so that if launch missions were failed, tremendous losses were brought about. Based on the reasons mentioned above, it is very important to enhance reliabilities of rocket engines and it is also significant to estimate their reliabilities correctly. Improvements of reliabilities concerning rocket engines are the key points in the world to minimize damage toward space activities.

Japan developed the world wide level large launch vehicle named H-2 with domestic technologies. H-2 Launch Vehicle was two-stage rocket augmented by a pair of large size solid motors and she had the launch capability of putting a 10 ton-class payload into the low earth orbit. The first stage of H-2 was propelled by the high pressure hydrogen/oxygen engine named LE-7, which was adopted two staged combustion cycle as same as Space Shuttle Main Engine developed by USA. During the developments of SSME, NASA encountered with serious engine system anomalies, which incurred whole damage to engines, because extremely high power and high stress stood right in the way of rocket engineers. Similarly, unexpected severe anomalies occurred in the development of LE-7 Engine, and yet the difficulties were finally overcome. After the qualification firing tests, the designs for flight engines were fixed and then the maiden flight of H-2 Launch Vehicle achieved successfully.

In the 7th flight of H-2 Launch Vehicle, material fatigue presumed to be caused by severe

cavitation vibration happened to the LE-7 Engine, and it resulted in the fatal flight failure. On the occasion of the flight accident, it was strongly recognized that to enhance the reliability of LE-7 Engine and to estimate its reliability correctly were very important for NASDA to maintain solid space transportation system.

In case of developments of high pressure large size rocket engines, there are noticeable characteristics concerning occurrences of engine troubles as follows. Establishment of start/stop sequence is difficult, therefore, transient troubles occur frequently in early phase of engine development. However, transient troubles decrease rapidly according as development phases progress, on the other hand, it is difficult to root out fatigue failures by the last phase of development, accordingly, they will cause flight missions to encounter serious failures. Most of causes of flight failures are occupied by engine troubles, because, it is difficult to estimate reliabilities of rocket engines correctly, in addition to that reliabilities of rocket engines are sometimes overestimated.

In this paper, according to these backgrounds above mentioned, aiming at enhancing reliabilities of rocket engines, first of all, the engine start anomaly, which occurred in the early phase of development of LE-7 Engine, was analyzed. In the next place, the fatigue damage to the hydrogen inducer presumed to be caused by severe fluid vibrations, occurred in the 7th flight of H-2 Launch Vehicle, was picked up as an important subject to be improved. Finally, in order to estimate reliabilities of rocket engines correctly, reliability estimation methods on LE-7 Engine and LE-7A Engine were studied.

(1) Start transient anomaly

High pressure rocket engines, which are adopted two staged combustion cycle, demonstrate good performance, but one of big disadvantages of this type of engine is the difficulty how to build up start transient, because turbine power is extremely small at the beginning of engine start. In the early phase of the development of LE-7 Engine, over spin phenomena were observed at rapid transient phase in both liquid hydrogen pump and liquid oxygen pump. In this case, the phenomena incurred serious damage to major parts of the engine. For a long time, the causes have not been clarified, so that failure analyses were conducted in this paper.

Liquid hydrogen has remarkable characteristics such that adiabatic pressurization of the fluid causes obvious temperature rise and its great rate of volume expansion causes low density of the fluid. According to the characteristics, decrease of pump efficiency causes obvious temperature rise which results in remarkable decrease of pump discharge pressure. Another over spin phenomenon was observed in the rapid flow rate change tests, which were conducted in order to investigate causes of the flight failure of the LE-7 Engine, and it was revealed that rapid fall of hydrogen flow rate caused temperature rise, first of all temperature at inlet of the first impeller, in the next place temperature at inlet and outlet of hydrogen pump. Based on this fact, it is strongly suggested that dynamical decrease of pump flow rate brings about decrease of pump efficiency, which causes excessive temperature rise up to the saturation of the pump fluid. Therefore, it is important to know the flow rates of both pumps at start transient phase to solve the over spin phenomena, but flow meters of the engine firing test facilities do not indicate flow rates of the pumps at start transient, because the test facilities have by-pass lines just front of the engine to keep inlet pressures constant during this phase. In order to get the flow rates of both pumps at start transient phase, flow resistance analyses were conducted. Also, evaluation equations that indicate shift of operational point of pumps were derived to estimate the excessive temperature rise of pump fluid. Finally, we get the conclusion that dynamical change of operational point brings about the over spin phenomenon observed in liquid hydrogen pump.

All the same, flow rate of oxygen pump at the start transient phase was studied, consequently, it was presumed that statical high flow rate over 140% brought about low discharge pressure of inducer, which caused impeller to be shortage of NPSH (net positive suction head), and it resulted in the over spin phenomenon observed in liquid oxygen pump.

(2) Fatigue induced by fluid vibration

Fluid energy of high pressure large size hydrogen engine is tremendously big, therefore, severe fluid vibration is easy to occur and it sometimes incurs occurrence of cracks caused by cumulated fatigue damage to limited life design parts. In case of the LE-7 Engine, it suddenly lost propulsive function in the midst of the 7th flight, in the result, the H-2 Launch Vehicle fell on the Pacific Ocean with the Multi-Function Transport Satellite, which was expected to fulfill very important role in Japan. The engine with malfunction was fortunately found at the sea bottom of 3000 meters deep, and the salvage of the LE-7 Engine was successively accomplished. Failure investigation was conducted and material fatigue was found at a blade of the hydrogen inducer. It was concluded that the flight failure was caused by multiple factors such as fluid vibration induced by rotating cavitations, coupling of fluid vibrations and others. So that background anomaly analyses toward the malfunction factors were conducted in this paper, in the result, countermeasures were proposed to prevent return accidents.

Improved engine named LE-7A was newly developed to propel the first stage of new lunch vehicle named H-2A and another severe fluid vibration, presumed to be cavitation surge, occurred in a hydrogen turbo-pump of LE-7A Engine. This phenomenon that caused severe damage to a bearing support of the hydrogen turbo-pump happened at the last phase of engine development, in other words qualification tests phase. In the case of LE-7A Engine as same as LE-7, inducer is connected directly with main rotor shaft, and then rotational tip speed of hydrogen inducer is the highest in the world. It is very difficult to conduct high power suction tests for LE-7A turbo-pump with use of liquid hydrogen, because, shortage of NPSH causes hydrogen turbo-pump to be over spin and results in centrifugal destruction. Some difficulties were overcome, and suction characteristics of the high-speed inducer were clarified.

Severe fluid vibration occurred in hydrogen inducer both of LE-7 and LE-7A Engine, however, vibration forces acting inducer blades can not be measured directly in hydrogen tests, therefore, relationship between vibration stress added to inducer blades and measured shaft vibration was investigated analytically.

(3) Reliability estimation methods

It is one of the difficult subjects even in advanced nations to estimate reliabilities of rocket engines correctly, because a lot of design changes are applied in development phases, and few mimic flight tests or full time firing tests called mission duty cycle tests are planned toward qualification model engines, which have same designs as flight model engines. Reliability estimation using the dispersive, binominal distribution method has been traditionally used in Japan to certify reliabilities of liquid rocket engines, but its estimation sometimes disagreed with failure rate of flight engines. LE-7 Engine was believed to have good reliability according to the results of ground firing tests, which cumulated about 300 firing tests and 15,200 burn times, however, the flight failure of LE-7 Engine occurred at the 7th flight of H-2 Launch Vehicle.

In order to take better results, the reliability growth model and the failure distribution method are applied in this paper to estimate the reliabilities of LE-7 and LE-7A Engine. The reliability growth model, proposed by Duane in 1962, gives good results in case that it is applied for early phase of development where design changes are adopted frequently. On the other hand, the failure distribution method gives good results in case that it is applied for the last phase of development where no design changes are adopted. According to these different methods, the reliabilities were presumed to be 94%～95% for LE-7 Engine and 98%～99% for LE-7A Engine. It was showed that the reliability of LE-7A Engine was improved 3～4 times better as compared with LE-7 Engine. Also, it was revealed by the failure distribution method that malfunctions caused by start and stop transient stress were solved in early phase of development, but malfunctions caused by fatigue damage remained unsolved up to the last phase of development, in the result, they should cause flight failures.

As mentioned above, correct estimation of reliability of a rocket engine is difficult work even in advanced nations and there are no reliable methods at the present situation, therefore it is important to estimate engine reliability with use of some different methods in order to make sure the reliability synthetically.

論文審査結果の要旨

液化水素を燃料とする二段燃焼サイクルのロケットエンジンは，極めて高い推進性能が得られるため，スペースシャトルやＨ－Ⅱなどの大型ロケット打ち上げ機の主推進装置として採用されている。このエンジンでは高圧ターボポンプ駆動用に大量の予燃焼ガスがタービンや主噴射器を高温かつ高速で流れるため，故障が発生した場合には重大事故に発展しやすく，打ち上げ時には衛星を含む機体の全損を招く。このため，エンジンで発生した故障を解析して原因を究明することや，エンジンの信頼度の適切な評価法を確立することは極めて重要である。本論文は，実際のエンジン開発において発生した始動時の過渡故障と定常作動時の疲労故障に関する解析と，故障率を的確に推定するための信頼度評価方法の改善に関する研究結果をまとめたもので，全編５章よりなる。

第１章は序論である。

第２章では，Ｈ－Ⅱ用のＬＥ－７エンジンの始動時に発生した故障のひとつである液化水素ポンプ回転数が増加するにもかかわらず吐出圧力が低下する空転現象について，過渡作動中のポンプ流量をエンジン各部の流動抵抗から算出し，故障要因解析と変動要因解析の手法を用いて，ポンプ効率の低下に伴う液温上昇が原因であることを明らかにしている。また，作動点が急速に変化する際のポンプ効率の変化方向を評価する式を導き，始動不良の対策を述べている。これは極低温ポンプの非定常作動特性に関する新たな知見であり，エンジンの始動方法を確立する上で重要な成果である。

第３章では，Ｈ－Ⅱ７号機で発生したＬＥ－７のフライト事故を招いた液化水素インデューサの疲労破損に関して，複数の直接要因を個別に分析し，背後要因を抽出して再発防止対策を考察している。また，大型高圧液化水素ポンプの吸込み試験を実施し，有害振動の発生領域を特定している。さらに，直接測定が困難なインデューサ羽根の振動と軸振動の関係を解析的に求め，軸振動の実測結果から羽根振動を推定している。これらは極低温ターボポンプの疲労破壊の原因究明と，今後の事故防止のために重要な成果である。

第４章では，設計変更や部品交換が頻繁に行われ，地上試験が実飛行時間に比べて短時間で行われることの多いロケットエンジンの信頼度評価法として，従来の二項分布法に代って信頼度成長法と故障分布法を取り上げてそれらの妥当性を検証している。ＬＥ－７エンジンの開発および実飛行時のデータに基づきに両手法を適用した結果，従来の二項分布法に比べてはるかに現実的な信頼度評価を得ている。また，現在運用されているＨ－ⅡＡ用のＬＥ－７Ａについてこれらの手法を適用して，その信頼度がＬＥ－７に比べて数倍向上していることを示している。これは宇宙開発の信頼度向上に有用な成果である。

第５章は結論である。

以上要するに本論文は，大型の液化水素ロケットエンジンの始動時および定常作動時に発生した主な故障の要因を解明するとともに，エンジンの信頼度評価の新しい評価法を提唱したもので，航空宇宙工学および推進工学の発展に寄与するところ少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。